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Calculating the Training Demand in an Expanding Military Organisation: an Analytical Solution

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ABSTRACT

The note presents an analytical solution for the calculation of training demand of an expanding military force. Two methods for deriving the solution for this problem have been proposed. The first method is based on a geometric series and demonstrates the method currently used by the Australian Army (a method the Army calls the "cyclic" process). The second method is based on a top down formulation of the same problem, and does not require infinite series and has fewer terms involved in the derivation of a solution. This method is potentially easier for Army officers to use for solving similar manpower planning problems in the future.

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Executive Summary

The work provides an analytical solution for the calculation of training demand of expanding military organisations.

A military manpower system is a form of closed system — trained staff and instructors for training are produced within the system except the lowest-rank newcomers. It is also hierarchical — higher rank staff are trained and promoted from lower rank staff. These features of military manpower systems complicate the calculation of training demands of an expanding military organisation. The complication arising from this closed manpower system can be stated in the following way: Expansion needs more trainees and hence more instructors from the combat force; a larger number of instructors reduces the assets of the combat force which creates further training demands; the further training demand needs to bring more staff from the combat force to do the instructing job. The calculation of the total training demand for this cyclic process poses some difficulty for the military situation and an analytical solution is presented in this report.

We present the solution to the training demand calculation for an expanding force for the typical Australian army four-rank training system. We also provide two methods for deriving a solution so that readers can apply the method they consider most appropriate to the particular training situation that they are considering.

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Contents

1. Background

Training Command – Army (TC-A) have tasked LOD, DSTO, to find a better way of calculating training demand for the training of Private (PTE) soldiers at the Army Recruitment Training Center (ARTC). Before this work was undertaken staff at TC-A were encountering a 'circular reference' error in their spreadsheet application when calculating numbers of trainees for an expanding course, trade, or wing of school. This report describes how TC-A's problem can be formulated as a geometric series, and hence an equation representing the solution can be written that does not contain circular references.

In this report we focus on the calculation of training demand at ARTC, although in principle the method described here could be applied to any training centre. The problem as described by TC-A consists of two parts:

- Computation of the steady-state training demand due to vacancies created by PTE soldiers being promoted, discharged or laterally transferred. This part of the calculation is straightforward, and TC-A staff consider this problem solved, as long as the yearly percentages of promotion, discharge, lateral transfer and training completion are known.
- Expansionary training demand due to increasing personnel in all four ranks of soldiers: PTE, Corporal (CPL), Sergeant (Sgt) and Warrant Officers (WO)[1]. TC-A staffs consider this computation to be not as well understood and so this part of the calculation is the focus of the discussion below.

Two aspects in the calculation of expanding training demand are considered by TC-A. These are:

- The demand caused by what the Army call the "suck-up" effect[2]. The effect occurs when there is an expansion in the number of staff in higher ranks and these positions must be filled from service staff in the lower ranks. TC-A have solved this problem for the four-rank case by explicitly summing the expansion demand for each rank.
- The demand caused by the "Dynamic"[3] effect, which is the *additional* training demand caused by vacancies in the combat force cause by shifting staff from the combat force to the training force to fill the increased demand in instructing jobs. This problem has not been solved by TC-A, because it leads to a large series (in theory this is an infinite series, but in practice the series can be terminated to provide an approximate answer). In this report we address this effect in the case for planning for the next course, that is we only investigate demand for one time period. We do not consider delays in the supply of staff from the combat force or potential subsequent long-term consequences that would occur if the

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[1] We confine our discussion to soldiers undergoing training. The conclusion is equally applicable to officer education and training.

[2] This is not a term that is normally used in the Army training literature, but rather a term used by the Army officers conducting training planning at TC-A.

[3] We adopt the word "Dynamic" as used by TC-A for easy communication while it is not really dynamic in the scientific sense because, as can be seen in the derivation later, the solution does not depend on time. For convenience, we refer to the *extra* training demand caused by the "Dynamic" effect simply as Dynamic Training Demand.

computation were iterated over a number of periods. The solution over a number of time-periods would require the solution to a set of difference (or differential) equations and at this stage is beyond the scope of this particular investigation, but it has been partially addressed in another report on manpower planning [1].

A solution to the "Dynamic" training demand is presented in the next section. The derivation for the solution is presented in the appendices so that TC-A can apply the methods in different scenarios.

2. Analytical Solution for the Calculation of "Dynamic" Training Demand

We frame the problem as follows:

The Army wants to ***expand and sustain at the expanded level, a combat force*** *that contains four ranks of* ***A, B, C*** *and* ***D****, with rank* ***D*** *the highest, by the amount of a, b, c and d, respectively. What are the training demands (number of trainees) TA, TB, TC and TD for each of these four ranks with given instructor/trainee ratios* R_a, R_b, R_c, R_d and *average graduation rates* G_a, G_b, G_c, G_d*?*[4]

We summarise the situation in Table 1:

Table 1: Training demand for expansion

Rank		***A***	***B***	***C***	***D***
Expansion		a	b	c	d
Raw Graduates Demand		a	b	c	d
Graduates Demand due to "suck-up" (Promotion)		b+c+d	c+d	d	
Initial Graduates Expected		A_0=a+b+c+d	B_0=b+c+d	C_0=c+d	$D_0 = d$
	Trainee A	**Trainee B**	**Trainee C**	**Trainee D**	
1st Training Demand	$A_1 = A_0 / G_a$	$B_1 = B_0 / G_b$	$C_1 = C_0 / G_c$	$D_1 = D_0 / G_d$	

The first two rows of Table 1 define the expansion requirements in the system. The new positions are to be filled by graduates. There are extra graduate demands because graduates (except the rank A) are from lower rank officers (and hence the Army's so-

[4] We assume the graduation rates are available by statistical average of historical data or from "expert opinion".

called "suck-up" effect). The "suck-up" effect is displayed in the 4th row, which adds to the "raw graduates demand" in the 3rd row to give the "Initial Graduates Expected". We note that the *actual* numbers of graduates depend the *actual* graduation rates g_a, g_b, g_c and g_d, which are random numbers.

We put the title of trainee category in the table to denote that while A rank trainees are recruited "off the street", the trainees at B, C and D ranks are from the personnel at ranks A, B and C in the combat force. The numbers of trainees required to deliver Initial Graduates Expected are displayed in the last row of the above table.

It is noted by TC-A, and has also been described using causal diagram analysis of system dynamics [1], that because of the closed nature of the military training system, more instructors are needed to train more trainees, which reduces the assets of the combat force. The reduction of the assets of the combat force creates a further training demand because these new vacancies now also need to be filled. That is, shifting personnel to work as instructors in training organisations, leads to a new requirement for more staff for the combat force.[5] This cyclic process causes Army some difficulty in computation because of cyclic references in their spreadsheets. Here we provide an analytical solution below and the derivation of this solution is given in the appendix.

Assume that all instructors are from one rank above[6], the total training demands, including the "Dynamic" Training Demands, for four ranks, TA, TB, TC and TD are:

$$TA = \frac{A_0}{G_a - R_a} + \frac{R_b B_0}{(G_a - R_a)(G_b - R_b)} + \frac{G_b R_c C_0}{(G_a - R_a)(G_b - R_b)(G_c - R_c)} + \frac{G_b G_c R_d D_0}{(G_a - R_a)(G_b - R_b)(G_c - R_c)(G_d - R_d)}, \quad (1)$$

$$TB = \frac{B_0}{G_b - R_b} + \frac{R_c C_0}{(G_b - R_b)(G_c - R_c)} + \frac{G_c R_d D_0}{(G_b - R_b)(G_c - R_c)(G_d - R_d)}, \quad (2)$$

$$TC = \frac{C_0}{G_c - R_c} + \frac{R_d D_0}{(G_c - R_c)(G_d - R_d)}, \text{ and} \quad (3)$$

$$TD = \frac{D_0}{G_d - R_d}, \quad (4)$$

where A_0, B_0, C_0, D_0 are Initial Graduates Expected defined in Table 1. Equations (1) – (4) are constrained by (see the Appendix):

$$0 < R_\lambda < G_\lambda \le 1 \qquad (\lambda = a, b, c, d), \quad (5)$$

which is applicable to all discussions in this work.

[5] We believe that there is an implicit policy decision that has been made in this view of the problem. This is addressed in the conclusion.

[6] This is, on average, an acceptable assumption according to TC-A.

3. Conclusion

An analytical solution is presented for TC-A's expansion problem. While the solution is based on the assumption that all instructors are from one rank above, the methods used in the derivation can be applied to any situations where the "dynamic" process is a consideration in calculation of training demands — that is, where an expanded force requires new instructors to come from operations, and where these additional vacancies require even more graduates to be recruited to fill the operational vacancies.

Two methods of deriving the solution for the "dynamic" process are presented in the Appendix for those interested in extending the solution beyond the assumptions of the original problem. However, it should be noted that the implementation of the solution in this report does not require an understanding of the derivations given in the main body of the report.

We note that the "Dynamic" training effect occurs because of an implicit training policy that is based on the assumption that an increase in instructors leads to a reduction in combat force that creates an immediate further training demand. We believe that this is only one of many possible training policies, and the solution given in this report may not be representative of an optimum policy. An analysis of this policy and its implications and other policy options that may be more efficient is expected to follow in another report.

4. Acknowledgements

We would like to thank Dr Chris Woodruff for providing some insightful comments and advice in the framing of this report. We also would like to thank Major Mark Nolan of TC-A for presenting the problem of training demand calculation and Ms Katie Walters in her involvement in discussions with TC-A in the articulation of this problem.

5. Reference

1. Wang, J., *A Review of Operations Research Applications in Manpower Planning and Potential Modelling of Military Training*. 2004, DSTO Technical Report, Submitted.

Appendix A: Methods of Derivation

Two methods used in solving the TC-A's problem are explained in this Appendix. The first method is based on an iterative formulation of the problem, while the formulation in the second appendix is based on a recursive definition. Although the body of this report contains a solution to the specific problem for the ARTC four-rank problem, the derivations are included here for future reference if other "dynamic" training problems are to be addressed. The iterative formulation of the problem exists as it more closely reflects the way Army currently view the Dynamic Training problem. However, this type of formulation leads to an expansion with many terms. Because of the large equations that result, we have also included a Recursive formulation of the problem. Although this is not the way the Army currently formulates the problem, it may be advantageous from an Army perspective since the intermediate steps do not lead to equations as large as those for the iterative formulation. The recursive formulation will also lead to derivations with fewer terms for other types of scenarios, for example, where instructors are not necessarily taken from the rank immediately above, but from several ranks above.

A.1. Iterative view of the expansion problem

Table 2 shows the cyclic process in the planning of "Dynamic" training demand.

Table 2: Iterative procedure for the calculation of "Dynamic" training demand

Rank		**A**	**B**	**C**	**D**
Expansion		a	b	c	d
Initial Graduates Expected		A_0 =a+b+c+d	B_0 =b+c+d	C_0 =c+d	D_0 =d
	Trainee A	**Trainee B**	**Trainee C**	**Trainee D**	
1st Training Demand	$A_1 = A_0 / G_a$	$B_1 = B_0 / G_b$	$C_1 = C_0 / G_c$	$D_1 = D_0 / G_d$	
Extra Instructors		$R_a A_1$	$R_b B_1$	$R_c C_1$	$R_d D_1$
2nd Training Demand	$A_2 = (R_a A_1 + R_b B_1 + R_c C_1 + R_d D_1) / G_a$	$B_2 = (R_b B_1 + R_c C_1 + R_d D_1) / G_b$	$C_2 = (R_c C_1 + R_d D_1) / G_c$	$D_2 = R_d D_1 / G_d$	
Extra Instructors		$R_a A_2$	$R_b B_2$	$R_c C_2$	$R_d D_2$
…….	…….	…….	…….	…….	…….
i-th Training Demand	$A_i = (R_a A_{i-1} + R_b B_{i-1} + R_c C_{i-1} + R_d D_{i-1}) / G_a$	$B_i = (R_b B_{i-1} + R_c C_{i-1} + R_d D_{i-1}) / G_b$	$C_i = (R_c C_{i-1} + R_d D_{i-1}) / G_c$	$D_i = R_d D_{i-1} / G_d$	
……	……	……	……	……	……
Total Training Demand	$TA = \sum_{i=1}^{\infty} A_i$	$TB = \sum_{i=1}^{\infty} B_i$	$TC = \sum_{i=1}^{\infty} C_i$	$TD = \sum_{i=1}^{\infty} D_i$	

Now we show that Equations (1) –(4) in the main body of the text can be derived by summing the four infinite series defined in the last row of Table 2. We do not display the intermediate step in the calculation because it is straightforward but tedious.

For rank D:

$$TD = (1 + r_d + r_d^{\ 2} + r_d^{\ 3} + ...)D_1 = (\sum_{n=0}^{\infty} r_d^{\ n})D_1 \equiv S(r_d)D_1 = \frac{D_1}{1 - r_d} = \frac{D_0}{G_d - R_d}, \quad \text{(A.1.1)}$$

where $r_d \equiv R_d / G_d$ and we have used the definition $D_1 = D_0 / G_d$ to get the final expression, which is Equation (4). We require $G_d > R_d > 0$ for TD to be positive and $1 \geq G_d$ by definition of graduation rate, which explains the constraint Equation (5). Notice that we have defined: $S(x) \equiv \sum_{n=0}^{\infty} x^n = \frac{1}{1 - x}$ $(x < 1)$ for convenience.

In the derivation below, we denote $r_\lambda \equiv R_\lambda / G_\lambda$ $(\lambda = a, b, c)$.

For rank C:

$$TC = S(r_c)C_1 + \frac{R_d S(r_c) S(r_d) D_1}{G_c} = \frac{C_0}{G_c - R_c} + \frac{R_d D_0}{(G_c - R_c)(G_d - R_d)}, \quad \text{(A.1.2)}$$

for $1 \geq G_c > R_c > 0$.

For rank B:

$$\begin{aligned} TB &= S(r_b)B_1 + \frac{R_c S(r_b) S(r_c) C_1}{G_b} + \frac{R_d S(r_b) S(r_c) S(r_d) D_1}{G_b} \\ &= \frac{B_0}{G_b - R_b} + \frac{R_c C_0}{(G_b - R_b)(G_c - R_c)} + \frac{G_c R_d D_0}{(G_b - R_b)(G_c - R_c)(G_d - R_d)} \end{aligned} \quad \text{(A.1.3)}$$

for $1 \geq G_b > R_b > 0$.

Finally for Equation (1) of rank A:

$$\begin{aligned} TA &= S(r_a)A_1 + \frac{R_b S(r_a) S(r_b) B_1}{G_a} + \frac{R_c S(r_a) S(r_b) S(r_c) C_1}{G_a} + \frac{R_d S(r_a) S(r_b) S(r_c) S(r_d) D_1}{G_a} \\ &= \frac{A_0}{G_a - R_a} + \frac{R_b B_0}{(G_a - R_a)(G_b - R_b)} + \frac{G_b R_c C_0}{(G_a - R_a)(G_b - R_b)(G_c - R_c)} \\ &+ \frac{G_b G_c R_d D_0}{(G_a - R_a)(G_b - R_b)(G_c - R_c)(G_d - R_d)} \end{aligned} \quad \text{(A.1.4)}$$

for $1 \geq G_a > R_a > 0$.

We present the iterative method here purely for illustrating the cyclic nature in the calculation of "Dynamic" training demand. As can be seen from the equations above, the solution requires expansion of nested series, and leads to algebra containing a large number of terms. The second method presented below avoids the problem of nested series and is recommended when applying this method to other problems.

A.2. Recursive view of the expansion problem

The method is to obtain the solution recursively, starting from the top rank D. The key equation to find Total Training Demand, TA, TB, TC and TD for ranks A, B, C and D, is the algebraic relation:

Total Graduates Expected = TTD0 + TTD1 + TTD2,

where TTD0 is the Initial Graduates Expected defined Table 1, TTD1 is the graduates expected to pay back instructors at higher ranks due to suck up and TTD2 is the graduates expected to pay back instructors at the current rank. See the concrete example below.

For rank D

$$G_d * TD = D_0 + R_d * TD, \tag{A.2.1}$$

which leads to

$$TD = \frac{D_0}{G_d - R_d}, \tag{A.2.2}$$

where $1 \geq G_d > R_d > 0$.

For the rank C, there is a need for the graduates of $R_c * TC$ instructors for rank C and the need for the graduates of $R_d * TD$ to fill vacancies created by C-rank staff becoming rank D trainees, which is due to the "suck-up" effect. Therefore, we have

$$G_c * TC = C_0 + R_d * TD + R_c * TC, \tag{A.2.3}$$

By solving Equation (A.2.3) for TC and then inserting Equation (A.2.2), TC reads

$$TC = \frac{C_0}{G_c - R_c} + \frac{R_d}{G_c - R_c} TD = \frac{C_0}{G_c - R_c} + \frac{R_d}{(G_c - R_c)(G_d - R_d)} D_0, \tag{A.2.4}$$

where $1 \geq G_c > R_c > 0$.

Note that the following relation is to be used in the rank-B derivation below

$$\begin{aligned} R_c * TC + R_d * TD &= \frac{R_c}{G_c - R_c} C_0 + [1 + \frac{R_c}{G_c - R_c}] * \frac{R_d D_0}{(G_d - R_d)} \\ &= \frac{R_c}{G_c - R_c} C_0 + \frac{G_c R_d}{(G_c - R_c)(G_d - R_d)} D_0 \end{aligned}. \tag{A.2.5}$$

For the rank B:

$$G_b * TB = B_0 + (R_c * TC + R_d * TD) + R_b * TB \tag{A.2.6}$$

Solving Equation (A.2.6) for TB and using Equation (A.2.5), we have:

$$TB = \frac{B_0}{G_b - R_b} + \frac{1}{G_b - R_b}(R_c * TC + R_d * TD)$$
$$= \frac{B_0}{G_b - R_b} + \frac{R_c}{(G_b - R_b)(G_c - R_c)} C_0 + \frac{G_c R_d}{(G_b - R_b)(G_c - R_c)(G_d - R_d)} D_0 \quad \text{(A.2.7)}$$

where $1 \geq G_b > R_b > 0$.

Again notice that the following relation is to be used in the subsequent rank-A calculation

$$R_b * TB + R_c * TC + R_d * TD$$
$$= \frac{R_b}{G_b - R_b} B_0 + [1 + \frac{R_b}{G_b - R_b}] \frac{R_c}{G_c - R_c} C_0 + [1 + \frac{R_b}{G_b - R_b}] \frac{G_c R_d}{(G_c - R_c)(G_d - R_d)} D_0 \quad \text{(A.2.8)}$$
$$= \frac{R_b}{G_b - R_b} B_0 + \frac{G_b R_c}{(G_b - R_b)(G_c - R_c)} C_0 + \frac{G_b G_c R_d}{(G_b - R_b)(G_c - R_c)(G_d - R_d)} D_0.$$

Finally for the rank A

$$G_a * TA = A_0 + (R_b * TB + R_c * TC + R_d * TD) + R_a * TA, \quad \text{(A.2.9)}$$

therefore:

$$TA = \frac{1}{G_a - R_a} A_0 + \frac{1}{G_a - R_a}(R_b * TB + R_c * TC + R_d * TD)$$
$$= \frac{1}{G_a - R_a} A_0 + \frac{R_b}{(G_a - R_a)(G_b - R_b)} B_0 + \frac{G_b R_c}{(G_a - R_a)(G_b - R_b)(G_c - R_c)} C_0 \quad \text{(A.2.10)}$$
$$+ \frac{G_b G_c R_d}{(G_a - R_a)(G_b - R_b)(G_c - R_c)(G_d - R_d)} D_0,$$

for $1 \geq G_a > R_a > 0$, where Equation (A.2.8) has been used in obtaining the final expression for TA in Equation (A.2.10).

It is quite clear from the equations from the recursive formulation that nested series have been avoided, and the equations have fewer terms. It is recommended that this formulation be used for future training situations.

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19. ABSTRACT

The note presents an analytical solution for the calculation of training demand of an expanding military force. Two methods for deriving the solution for this problem have been proposed. The first method is based on a geometric series and demonstrates the method currently used by the Australian Army (a method the Army calls the "cyclic" process). The second method is based on a top down formulation of the same problem, and does not require infinite series and has fewer terms involved in the derivation of a solution. This method is potentially easier for Army officers to use for solving similar manpower planning problems in the future.